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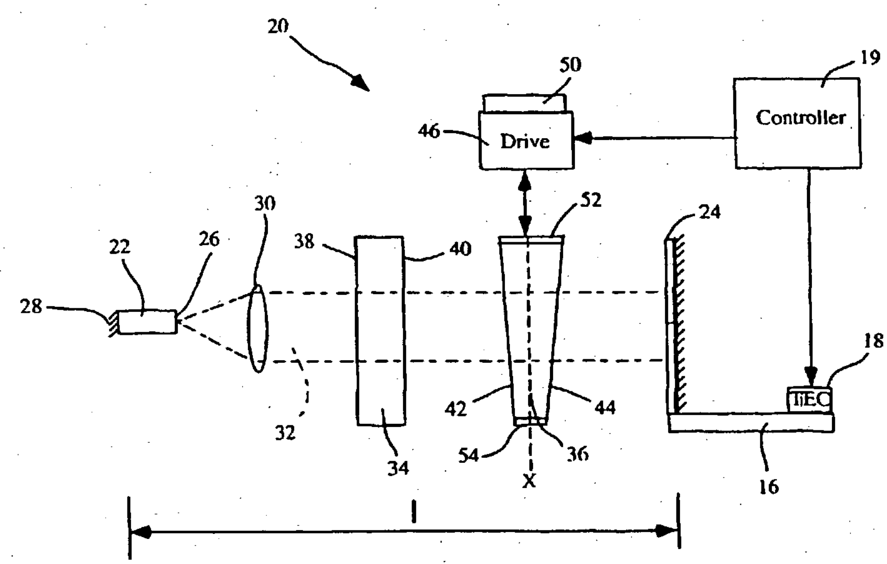
(54) Title: LASER APPARATUS WITH ACTIVE THERMAL TUNING OF EXTERNAL CAVITY



(57) Abstract: A laser apparatus (20) and method that uses active thermalization of a reflective element to minimize losses and provide wavelength stability. The laser comprises first and second reflectors (24,28) defining an external cavity, and a compensating member (16) coupled to at least one of the reflectors (24) and configured to thermally position one reflector (24) with respect to the other reflector (28). The thermal positioning may be carried out by a thermoelectric controller (18) operatively coupled to the compensating member (16) and configured to thermally adjust the compensating member (16) by heating or cooling thereof. The laser apparatus (20) may comprise a gain medium (22) having first and second output facets (26,28) and emitting a coherent beam

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LASER APPARATUS WITH ACTIVE THERMAL TUNING OF EXTERNAL CAVITY

BACKGROUND OF THE INVENTION

Fiberoptic telecommunications are continually subject to demand for increased bandwidth. One way that bandwidth expansion has been accomplished is through dense wavelength division multiplexing (DWDM) wherein multiple separate data streams exist concurrently in a single optical fiber, with modulation of each data stream occurring on a different channel. Each data stream is modulated onto the output beam of a corresponding semiconductor transmitter laser operating at a specific channel wavelength, and the modulated outputs from the semiconductor lasers are combined onto a single fiber for transmission in their respective channels. The International Telecommunications Union (ITU) presently requires channel separations of approximately 0.4 nanometers, or about 50 GHz. This channel separation allows up to 128 channels to be carried by a single fiber within the bandwidth range of currently available fibers and fiber amplifiers. Improvements in fiber technology together with the ever-increasing demand for greater bandwidth will likely result in smaller channel separation in the future.

The drive towards greater bandwidth has led to use of precision, wavelength-specific DWDM devices that require careful adjustment in order to provide a transmission output at the narrowly separated channel spacings. As tunable elements are configured for narrower channel separation, decreasing component tolerances and thermal fluctuation become increasingly important. In particular, tunable telecommunication transmitter lasers are susceptible to non-optimal positioning of tunable elements due to environmental thermal fluctuation that results in wavelength instability and reduced transmitter output power. There is currently a need for a telecommunication transmitter laser which provides for simple and accurate adjustment of tunable elements to reduce losses and wavelength stability associated with thermal fluctuation and other environmental factors present during laser operation.

SUMMARY OF THE INVENTION

The invention is a laser apparatus and method that uses active thermal adjustment of a laser cavity reflective element to minimize losses and provide wavelength stability. The apparatus of the invention, in general terms, is a laser comprising first and

detector may be an optical detector positioned to monitor optical output from the external cavity, or may be a voltage sensor positioned to monitor voltage across the gain medium. Error signals derived from the output of the detector may be utilized by a controller to adjust the external cavity by thermal positioning of the end mirror via heating or cooling the compensating member.

The laser may further comprise a dither element operatively coupled to the external cavity and configured to introduce a detectable frequency modulation into the external cavity. The dither element may be associated with the end mirror or located elsewhere in the external cavity. The frequency modulation introduced by the dither element results in a known or predictable intensity and/or phase variation in optical feedback from the external cavity to the gain medium. This intensity and/or phase variation from the dither is detectable in either the monitored voltage across the gain medium or the optical output of from the external cavity. The positioning of the end mirror via heating or cooling the compensating element effects the phase and intensity of the modulation signal, and the magnitude and phase of the modulation signal as detected via voltage or optical power modulation may be used to generate an error signal. The error signal is usable to position or otherwise adjust the end mirror to null the error signal according to thermal positioning of the end mirror by the compensating member.

The method of the invention is a method of laser operation that comprises, in general terms, providing first and second reflectors that define a laser cavity, and adjusting the laser cavity by thermally adjusting a compensating member coupled to at least one of the reflectors. The thermally adjusting of the compensating member comprises heating or cooling the compensating member with a thermoelectric controller coupled to the compensating member. The method may further comprise passively athermalizing or thermally stabilizing the laser cavity, and monitoring external losses associated with the laser cavity. The thermal adjusting may be carried out according to error signals derived from the monitoring of losses associated with the external cavity. The method may further comprise introducing a frequency modulation into the external cavity, and deriving error signals according to amplitude and phase of detected frequency modulation.

should be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting.

Referring now to FIG. 1, there is shown an external cavity apparatus 10 that employs thermal control of the external cavity optical path length in accordance with the invention. The apparatus 10 includes a first reflective element 12 and a second reflective element 14 which together define an external cavity of optical path length *l*. A gain medium (not shown) may be positioned between reflective elements 12, 14, or one of reflective elements 12, 14 may comprise a mirrored or partially mirrored surface of a gain medium as described further below. Various other optical components usable in external cavity lasers, such as a grid generator and channel selector (not shown) may also be positioned within the external cavity defined by reflectors 12, 14, as also described below. Reflective elements 12, 14 may be mounted on or associated with a common base (not shown).

First reflector 12 is coupled or joined to a compensating element or member 16 that is configured to positionally adjust reflective element 12 by active thermal control. Compensating member 16 is made from a material having a high, or relatively high, coefficient of thermal expansion (CTE), such as aluminum, zinc or other metal or metal alloy. For example, aluminum has a CTE with 24 * 10^-6/°C and zinc with 30.2 * 10^-6/°C. KOVAR® alloy, which may also be used, has a moderate coefficient with 4.8 * 10^-6/°C. Various other materials of suitable CTE will suggest themselves to those skilled in the art upon review of this disclosure.

The material of compensating member 16 ideally will be thermally conductive so that member 16 can be rapidly heated and cooled. A thermoelectric controller 18 is operatively coupled to compensating member 16 and is configured to heat or cool compensating member 16, which in turn undergoes corresponding thermal expansion or contraction to positionally adjust the reflector 12 coupled to compensating member 16.

Thus, heating of compensating member 16 by thermoelectric controller 18 results in thermal expansion of compensating member 16 that moves reflector 12 closer to reflector 14 to shorten optical path length *l*. Cooling of compensating member 16 by thermoelectric controller 18 results in a thermal contraction of compensating member 16 such that reflector 12 is moved away from reflector 14 to increase external cavity optical

Other wavelength grids may alternatively be selected. Grid etalon has a free spectral range (FSR) that corresponds to the spacing between the grid lines of the ITU grid, and the grid etalon 34 thus operates to provide a plurality of pass bands centered on each of the gridlines of the wavelength grid. Grid etalon 34 has a finesse (free spectral range divided by full width half maximum or FWHM) that suppresses neighboring modes of the external cavity laser between each channel of the wavelength grid.

Grid etalon 34 may be a parallel plate solid, liquid or gas spaced etalon, and may be tuned by precise dimensioning of the optical thickness between faces 38, 40 by thermal expansion and contraction via temperature control. The grid etalon 34 may alternatively be tuned by tilting to vary the optical thickness between faces 38, 40, or by application of an electric field to an electrooptic etalon material. Grid etalon 34 also may be actively tuned to selected communication grids as described in U.S. Patent Application Ser. No. 09/900,474 entitled "External Cavity Laser with Continuous Tuning of Grid Generator" to inventor Andrew Daiber, filed concurrently herewith, the disclosure of which is incorporated herein by reference.

Wedge etalon channel selector 36 also acts as an interference filter, with non-parallel reflective faces 42, 44 providing a tapered shape. Wedge etalon 36 may comprise a tapered transparent substrate, a tapered air gap between the reflective surfaces of adjacent transparent substrates, or a thin film "wedge interference filter. Wedge etalon 26 as shown in FIG. 2 is only one tunable element that may be used in accordance with the invention in an external cavity laser. Wedge etalon 26 may be replaced with a variety of tunable elements other than an etalon, such as grating devices and electro-optic devices. The use of an air gap wedge etalon as a channel selector is described in U.S. Patent No. 6,108,355, wherein the "wedge" is a tapered air gap defined by adjacent substrates. The use of pivotally adjustable grating devices as channel selectors tuned by grating angle adjustment and the use of an electro-optic tunable channel selector in an external cavity laser and tuned by selective application of voltage are described in U.S. Patent Application Ser. No. 09/814,646 to inventor Andrew Daiber and filed on March 21, 2001. The use of a translationally tuned graded thin film interference filter is described in U.S. Patent Application Ser. No. 09/814,646 and in U.S. Patent Application Ser. No. 09/900,412 entitled "Graded Thin Film Wedge Interference Filter and Method of Use for Laser Tuning" to inventors Hopkins et al., co-filed herewith. The aforementioned disclosures are incorporated herein by reference.

Wedge etalon 36 is positionally tuned via a tuning assembly that comprises a drive element or wavelength tuner 46 structured and configured to adjustably position wedge etalon 36 according to selected channels. Tuner 46 may comprise a stepper motor together with suitable hardware for precision translation of wedge etalon 36. Tuner 46 may alternatively comprise various types of actuators, including, but not limited to, DC servomotors, solenoids, voice coil actuators, piezoelectric actuators, ultrasonic drivers, shape memory devices, and like linear actuators known in the art.

Wavelength tuner 46 is operatively coupled to a controller 19 that provides signals to control the positioning of wedge etalon 36 by tuner 46. Controller 19 may include a data processor and memory (not shown) wherein are stored lookup tables of positional information for wedge etalon 36 that correspond to selectable channel wavelengths. Controller 19 as shown is also coupled to thermoelectric controller 18 and provides controlling instructions to both the wavelength tuner 46 and thermoelectric controller 18. A separate controller (not shown) may alternatively be used for wavelength tuner 46, and may be internal to tuner 46, or may be external and shared in other component tuning and servo functions of external cavity laser 20.

When external cavity laser 20 is tuned to a different communication channel, controller 19 signals tuner 46 according to positional data stored in the look up table, and tuner 46 translates or drives wedge etalon 36 to the correct position wherein the optical thickness of the portion of the wedge etalon 36 positioned in optical path 32 provides constructive interference which supports the selected channel. A linear encoder 50 may be used in association with wedge etalon 36 and tuner 46 to ensure correct positioning of wedge etalon 36 by tuner 46.

Wedge etalon 36 may include opaque regions 52, 54 at its ends that are optically detectable and which serve to verify the position of wedge etalon 36 when it has been positionally tuned to its longest or shortest channel wavelength. Opaque regions 36 provide an additional encoder mechanism usable in the positional tuning of wedge etalon 36. When wedge 36 is moved into a position such that one of opaque regions 52, 54 enters optical path 32, the opaque region 52, 54 will block or attenuate the beam along optical path. This attenuation of light is detectable, as described further below. Since the location of opaque regions 52, 54 on wedge etalon 36 can be determined with precision, controller 38

adjacent channels or modes is shown. The external cavity pass bands PB1 shown in FIG. 3A-3C are omitted from FIG. 4A-4C for clarity. The grid etalon 34 selects periodic longitudinal modes of the external cavity corresponding to the grid channel spacing while rejecting neighboring modes. The wedge etalon 36 selects a particular channel in the wavelength grid and rejects all other channels. The selected channel or lasing mode is stationary at one particular channel for filter offsets in the range of approximately plus or minus one half channel spacing. For larger channel offsets the lasing mode jumps to the next adjacent channel.

In FIG. 4A, the wedge etalon pass band PB3 is centered with respect to the grid channel at 1549.5 nm. The relative gain associated with pass band PB2 at 1549.5 nm is high, while the relative gain levels associated with adjacent pass bands PB2 at 1549.0 nm and 1550.0 nm are suppressed relative to the selected 1549.5 nm channel. The gain associated with pass bands PB2 at 1550.5 nm and 1548.5 nm is further suppressed. The dashed line indicates the relative gain for pass bands PB2 without suppression by wedge etalon 26.

FIG. 4B shows the wedge etalon pass band PB at a position in between the channels at 1549.5 nm and 1550.0 nm, as occurs during channel switching. The relative gain associated with pass bands PB2 at 1549.5 nm and 1550.0 are both high, with neither channel suppressed. The relative gain levels associated with pass bands PB2 at 1549.0 nm and 1550.5 nm are suppressed relative to the 1549.5 nm and 1550.0 nm channels. The dashed line indicates the relative gain for pass bands PB2 without suppression by wedge etalon 26.

FIG. 4C shows the wedge etalon pass band PB3 centered with respect to the grid channel at 1550.0 nm, with the relative gain associated with the pass band PB2 at 1550.0 nm being high, while the relative gain levels associated with adjacent pass bands PB2 at 1549.5 nm and 1550.5 nm are suppressed relative to the selected 1550.0 nm channel, and the gain associated with pass bands PB2 at 1551.0 nm and 1549.0 nm is further suppressed. Again, the dashed line indicates the relative gain for pass bands PB2 without suppression by wedge etalon 26.

The external cavity pass bands PB1, while not shown in FIG. 4A-FIG. 4C, are an important consideration in the tuning of external cavity laser 20. Ideally, one of the

various metals, metal alloys, metal nitrides, metal carbides and/or blends, composites, mixtures or alloys thereof.

Electrodes 66, 68 are coupled to gain medium 12, with electrode 66 operatively coupled to a drive current source 70, and with electrode 68 suitably grounded. Drive current source 70 is operatively coupled to controller 19, and controller 19 may regulate the current delivered to gain medium 22 as required. A voltage sensor 72 is operatively coupled to electrode 66 and to controller 19. Voltage sensor 72 is configured to monitor the voltage across gain medium 22 during laser operation and communicate a sensor output to controller 19 that is indicative of the monitored voltage. Since optical feedback from end mirror 24 is reflected back into gain medium 22 through facet 26, the monitored voltage is indicative of optical losses associated with the external cavity defined by end mirror 24 and gain medium facet 28. Error signals may thus be derived from the output of voltage sensor 72 which may be used by controller 19 to re-position end mirror 24, by heating or cooling of compensating member 16, to adjust the external cavity and null out the error signal. Optical feedback from the faces 38, 40 of grid etalon 32, and faces 42, 44 of wedge etalon 36 are also reflected back into gain medium 22, and in some embodiments the sensed voltage across gain medium may provide error signals usable for adjustment of grid etalon 34 via thermoelectric controller 64, and wedge etalon 36 by tuner 46.

In the operation of laser 56, current is applied to gain medium 22 by drive current source 70 via electrodes 66, 68, according to instruction from controller 19. Voltage across gain medium 22 is measured by voltage sensor 72 and communicated to controller 19. Various instances may arise in which the external cavity pass bands PB1 are not optimally positioned with respect to the selected grid etalon pass band PB2 and wedge etalon pass band PB3, either due to external environmental factors such as vibration or thermal fluctuation, or due to a channel changing event wherein wedge etalon 36 is intentionally positioned to select a different transmission channel as described above. In such instances, losses will arise in the external cavity defined by end mirror 24 and gain medium facet 28, and controller 19 may selectively instruct the heating or cooling of compensating member 16 by thermoelectric controller 18 to position or tune end mirror 24 to minimize the external cavity loss and null the error signal.

Modulation of the optical path length l via frequency dither introduced by element 58 produces intensity variations in the output power of external cavity laser 56, as noted above. This modulation is detectable in the monitored voltage across gain medium 22, due to optical feedback thereinto from the external cavity. These intensity variations will decrease in magnitude and phase error as a laser cavity mode or pass band is aligned with the center wavelength of the pass bands defined by grid generator 34 and channel selector 36. In other words, the intensity variations and phase error in the modulation signal are minimal or nominally zero when pass bands PB1, PB2 and PB3 are optimally aligned as shown in FIG. 3A-3C. The use of intensity variation and phase error in the modulated signal with respect to error signal determination is described further below with reference to FIG. 6.

During operation of the external cavity laser 56 with dither element 74, voltage signals from voltage sensor 72 are communicated to controller 19, which derives an error signal from the modulation introduced by the frequency dither, and communicates a compensation signal to thermoelectric controller 18, which heats or cools compensating member 16, which in turn expands or contracts accordingly to tune or adjust the optical path length l by positionally adjusting end mirror 24. Controller 19, during the operation of laser 56, may also control the drive current to gain medium 12 and the positioning of channel selector 36 by tuner 46. Controller 19 may also control the temperature of grid etalon 34 via thermoelectric controller 66.

Referring also to FIG. 6, the relationship of the dither modulation signal introduced to an external cavity with respect to the detected voltage modulation across gain medium 12 is illustrated graphically as wavelength versus relative intensity. FIG. 6 shows a grid etalon pass band PB2, together with frequency or dither modulation signals 76A, 76B, 76C corresponding to external cavity laser modes 78A, 78B and 78C respectively. Frequency modulation signals 76A-C are introduced to the laser external cavity by voltage modulation of electro-optic element 58 in the manner described above. As shown in FIG. 6, laser mode 78A is off-center with respect to the center of pass band PB2 towards the shorter wavelength side of pass band PB2, while laser mode 78B is located at about the center wavelength of pass band PB2, and laser mode 78C is located on the longer wavelength side of pass band PB2. Laser mode wavelength 78B corresponds to a wavelength lock position and represents an optimal loss profile for the external cavity. Laser modes 78A and 78B are off-center with respect to pass band PB2 and result in non-optimal cavity loss profiles which

a dither frequency of around 20 KHz is effective for the specific tuning shown in FIG. 4A-4C.

The active thermal control for positioning of end mirror 24 as described above may be used together with passive thermal stabilization of the external cavity of laser 56 and the optical components therein as well. Passive thermal stabilization or "athermalization" comprises, in its simplest form, the use of passive elements of differing coefficients of thermal expansion (CTE) joined end-to-end and having lengths that are inversely proportional in ratio to the ratio of the CTEs of the elements. The distance between the unjoined ends of the elements, in this instance, will remain constant, independent of temperature, although the length of the individual elements will vary with varying temperature. Numerous complex optical structures have been built using the above principle. The principles of passive athermalization are well known and are described in Yoder et al.,"Opto-mechanical Systems Design" Second Edition, 1993, Marcel Dekker Inc., Chapter 14; "Optical Instrument Structural Design", the disclosure of which is incorporated herein by reference.

The use of passive thermal stabilization alone in an external cavity laser, without active thermal control of the external cavity as provided by the invention, is beneficial but may be difficult to implement accurately in certain laser architectures. Thus, changes in laser properties may still result due to thermal gradients and temperature variations that cannot be easily compensated by passive thermal stabilization. The invention provides for the detection of such changes in laser properties by voltage monitoring or otherwise, and then varying the temperature of a structural member associated with the external cavity according to the detected variation to adjust the external cavity optical path length as described above.

Temperature changes during laser operation affect the overall cavity length and index of refraction of the cavity and components therein, which will in turn result in variations in output wavelength and optical losses associated "unlocking" of the external cavity modes from the selected transmission channel wavelength. As the optical path length of the external cavity varies with respect to temperature, the integral number of half-wavelengths that may be supported in the cavity varies. The optical path length of an external cavity is a function of the physical thickness of each element, including optical

components of the laser 82, including gain medium 22, channel selector 36, collective optical elements 86, and air gaps, La_1, La_2, La_3 between the aforementioned elements. The optical thickness or path length through gain medium 22 is L_d, while the optical path length through elements 86 is L_1, and the optical path length through channel selector 36 is L_t. The optical path length through the air gap between gain medium 22 and optical elements 86 is La_1, while the optical path length through the air gap between optical elements 86 and channel selector 36 is La_2, and the optical path length between channel selector 36 and end mirror 24 is La_3. Since all elements of laser 82 are directly or indirectly coupled to base 58, their relative physical separation will typically increase as the temperature of base 58 increases. This may in turn result in variation of the cavity optical path length L_{Opl}.

The optical path length of an element generally is equal to the product of its refractive index and its dimension along the optical path. The optical path length of an external cavity laser is a sum of the products of indices of refraction and optical thicknesses of the various elements present in the optical path across the external cavity, including air present within the cavity. The optical path length of an external cavity laser thus can be shown as

$$L_{Opl} = \sum n_i \bullet l_i \tag{1}$$

wherein n_i is the index of refraction of each element and l_i is the thickness of the element along the optical path. A lower case *l* as used herein references the physical dimension of an element, while an upper case *L* references an optical dimension. The integer number of half-wavelengths supported by an element with fixed end points increases as the refractive index of the element increases, as predicted by Huygens principle. This results from the observation that light travels more slowly in media of higher refractive index and the wave peaks are correspondingly more closely packed. Thus, over an identical distance, an element with a higher index of refraction supports a greater number of wavelengths, and the optical path length, rather than the physical path length, is a more accurate measure of the integral number of half wavelengths that may be supported by an external cavity.

$$0=\frac{dL_{Opl}}{dT}=\sum\frac{d(n_i \bullet l_i)}{dT}=\sum\left(n_i \bullet \alpha i+\frac{dni}{dT}\right)\bullet li$$

(2)

In equation (2), the requirement that the rate of change of the optical path length L_{Opl} with respect to temperature be zero satisfies the condition that the optical path length be temperature invariant. The optical path length is expressed as the sum of the derivatives of the product of the refractive index n_i of each element, the thermal expansion coefficient α_i of each element, and the physical length l_i of each element. As noted above, the various elements of the external cavity include the gain medium 22, channel selector 36, other optics 86, and the air or other gas present in the optical path.

The optical path of the external cavity laser 82 in FIG. 7A is the sum of the optical length of the individual segments of which it is composed, including the regions of air or other gas separating the optical components. This relationship may be expressed in the solution to equation (1) shown in equation (3)

$$L_{Opl} = L_d + L_l + L_t + L_{a123} = n_d l_d + n_l l_l + n_t l_t + n_a l_{a123}$$

(3)

The air gap length, l_{a123}, is affected by expansion and contraction of base 58 and compensating member 18, and the air gap can be expressed in terms of the dimensions of base 58, l_{Fl}, and the dimensions of compensating member 18, l_c. Equation (3) can then be expressed as

$$L_{Opl} = n_d l_d + n_l l_l + n_t l_t + n_a(l_{Fl} - l_d - l_l - l_t - l_c)$$

(4)

Equation (4) can be expressed as equation (5) below, to show the optical path length in terms of the optical length L_{Fl} of base 58, the additional optical length LO produced by the optical elements 86 in the cavity, and the optical length L_C of the compensating element 18.

$$L_{Opl} = L_d + L_l + L_t + L_{a124} = n_d l_d + n_l l_l + n_t l_t + n_a l_{a124} \tag{9}$$

As noted above, the air gap length l_{a123} is affected by expansion and contraction of base 58 as well as compensating member 18. In this case, however, the expansion of compensating member 18 has an opposite effect to that noted for FIG. 7A. The air gap length can be expressed in terms of the dimension l_{F1} of base and the dimension L_c of compensating member 18. The solution of equation (9) can be shown as equation (10).

$$L_{Opl} = n_d l_d + n_l l_l + n_t l_t + n_a(l_{F1} - l_d - l_l - l_t + l_c) \tag{10}$$

Equation (10) can be expressed in terms of the optical length L_{F1} of base 58, the additional optical length L_O provided by optics 86, and the optical length L_C of compensating member 18.

$$L_{Opl} = [n_a l_{F1}] + [(n_d - n_a) l_d + (n_l - n_a) l_l + (n_t - n_a) l_t] - [n_a l_c] \tag{11}$$

or, more simply,

$$L_{Opl} = L_F + L_O + L_C \tag{12}$$

Finding the derivative of LOpl and setting it equal to zero provides a solution for the derivative of the of the optical length $L_{C'}$ of compensating element 18 in terms of the sum of the derivative L_F' of the optical length of base 58, and L_O' of the optical components 86 as shown in equation (13) below. The coefficients of thermal expansion α_c, α_F, α_d, α_l for compensating element 18, base 58, gain medium 22, optics 86 and channel selector 36 respectively, may be used in solving the derivative. In addition, the indices of refraction n_a, n_d, n_l, and n_t for air, gain medium 22, optical elements 86 and channel selector 36 respectively are used to obtain the derivative

CLAIMS

What is claimed is:

1. A laser apparatus, comprising first and second reflectors defining a laser cavity, and a compensating member coupled to at least one of said reflectors and configured to thermally position one of said reflectors with respect to the other said reflector.

2. The laser apparatus of claim 1, wherein said compensating member is coupled to said first reflector and configured to position said first reflector with respect to said second reflector.

3. The laser apparatus of claim 1, further comprising a thermoelectric controller operatively coupled to said compensating member and configured to thermally adjust said compensating member.

4. The laser apparatus of claim 2, further comprising a gain medium having first and second output facets, said first output facet emitting a coherent beam along an optical path, said first reflector positioned in said optical path, said second output facet defining said second reflector, said first reflector and said second output facet defining said laser cavity.

5. The laser apparatus of claim 2, wherein said compensating member is thermally conductive.

6. The laser apparatus of claim 2, wherein said compensating member has a high coefficient of thermal expansion.

7. The laser apparatus of claim 4, wherein said gain medium and said first reflector are passively athermalized with respect to each other.

8. The laser apparatus of claim 1, further comprising:

(a) a detector associated with said external cavity and configured to detect losses associated with said external cavity; and

compensating member being dimensioned and configured to passively athermalize said external cavity.

15. The external cavity laser apparatus of claim 10, further comprising:

(a) a detector associated with said external cavity and configured to detect losses associated with said external cavity; and

(b) a controller operatively coupled to said compensating element and said detector and configured to thermally adjust said compensating member according to error signals derived from said detector.

16. The external cavity laser apparatus of claim 15, wherein said detector is a voltage detector positioned to monitor voltage across said gain medium.

17. The external cavity laser apparatus of claim 15, further comprising a dither element operatively coupled to said external cavity and configured to introduce a frequency modulation to external cavity.

18. The external cavity laser apparatus of claim 10, wherein said compensating member comprises a material having a high coefficient of thermal expansion.

19. The external cavity laser apparatus of claim 18, wherein said compensating member is thermally conductive.

20. An external cavity laser apparatus, comprising:

(a) a gain medium including first and second output facets, said gain medium emitting a coherent beam from said first output facet along an optical path;

(b) an end mirror positioned in said optical path, said end mirror and said second output facet defining an external cavity;

(c) a compensating member coupled to said end mirror, said compensating member having a first coefficient of thermal expansion;

(d) a thermal controller coupled to said compensating member and configured to positionally adjust said end mirror by thermally controlling said compensation member; and

(e) a thermally conductive base, said thermally conductive base having a second coefficient of thermal expansion, said gain medium coupled to said base, said thermal

28. The method of claim 26, further comprising passively athermalizing said laser cavity.

29. The method of claim 26, further comprising monitoring losses associated with said laser cavity.

30. The method of claim 29, wherein said thermally adjusting is carried out according to error signals derived from said monitoring of said losses associated with said laser cavity.

31. The method of claim 29, further comprising introducing a frequency modulation into said laser cavity.

32. A method for generating a tunable coherent optical output, comprising:

(a) providing an external cavity laser having a gain medium with first and second output facets and emitting a coherent beam from said first output facet along an optical path, and an end mirror positioned in said optical path, said end mirror and said second output facet defining an external cavity; and

(b) adjusting said optical cavity by thermally adjusting a compensating member coupled to said end mirror.

33. The method of claim 32, wherein said thermally adjusting said compensating member comprises heating or cooling said compensating member with a thermoelectric controller coupled to said compensating member.

34. The method of claim 32, further comprising passively athermalizing said external cavity.

35. The method of claim 32, further comprising monitoring external losses associated with said external cavity.

36. The method of claim 35, wherein said monitoring comprising monitoring voltage across said gain medium.

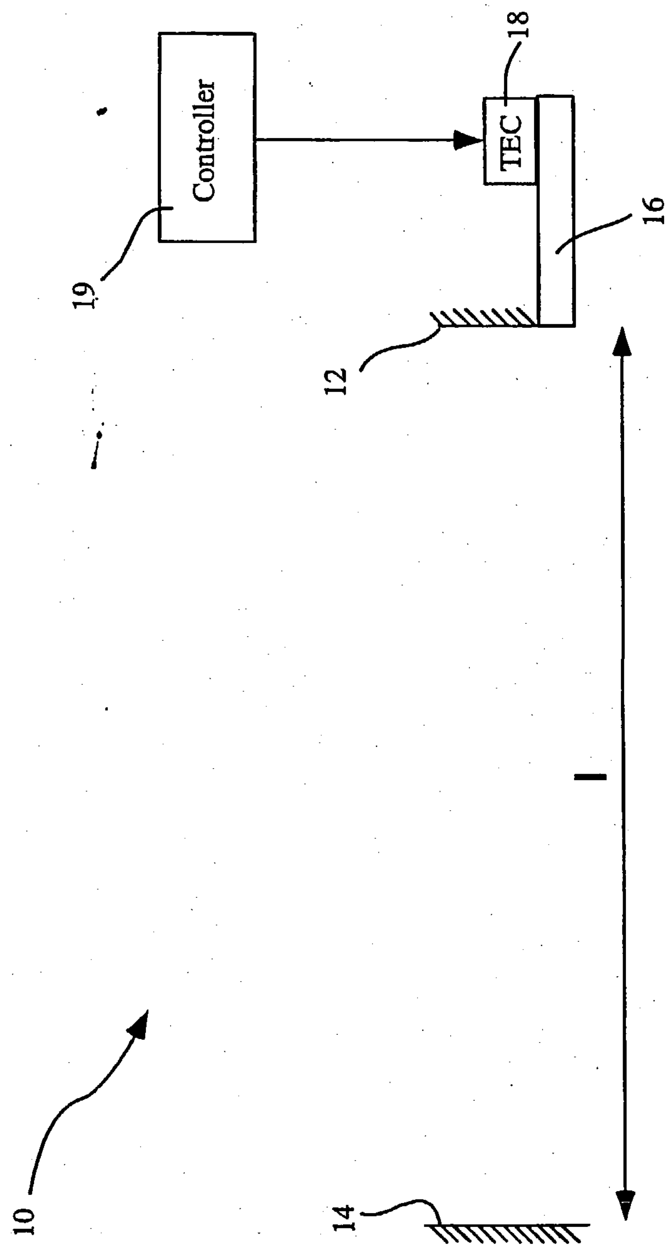
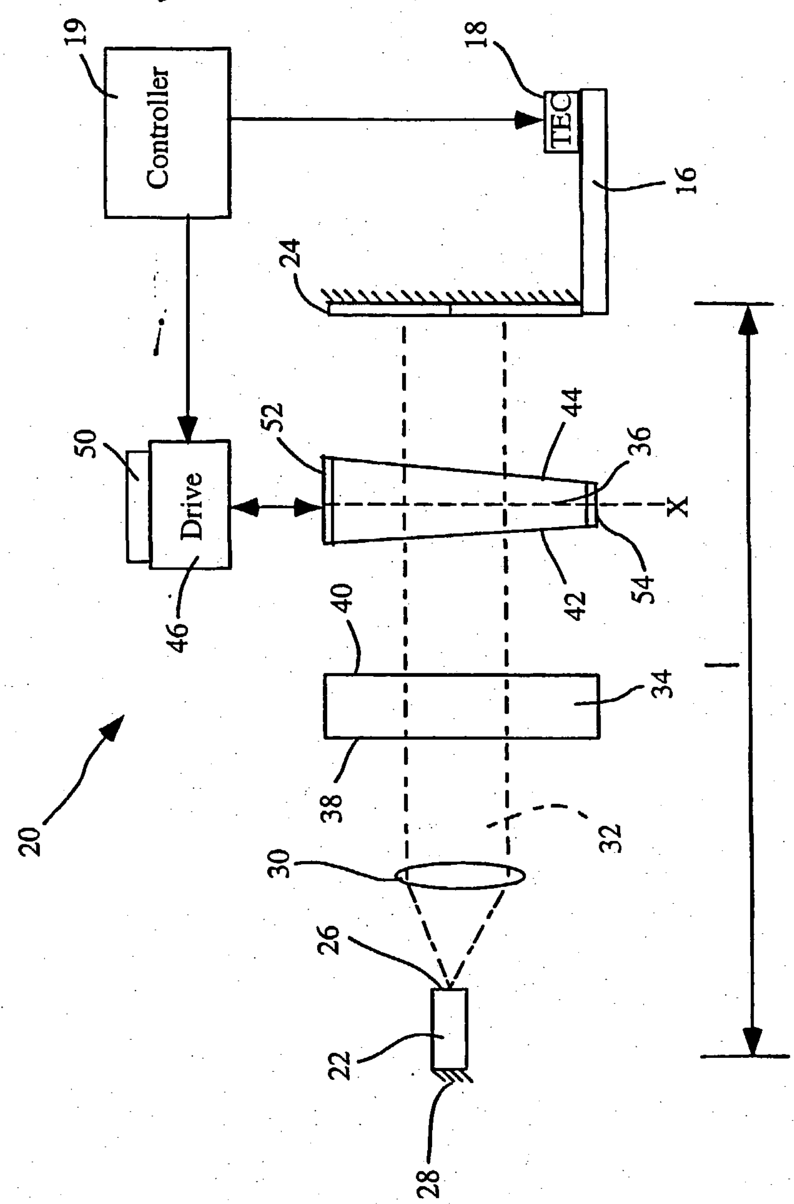


Fig. 1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TEC
18
16
24
Drive
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46
52
44
36
X
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34
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20
32
30
26
22
28
l

Fig. 2

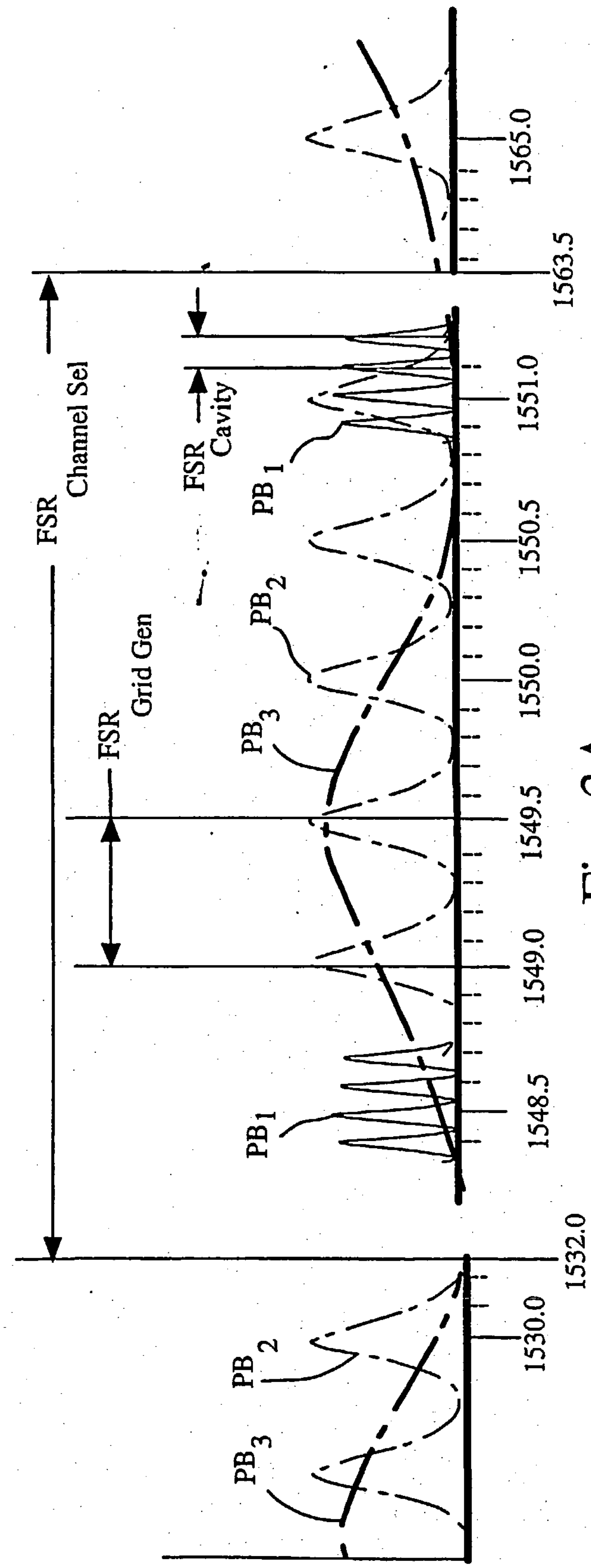


Fig. 3A

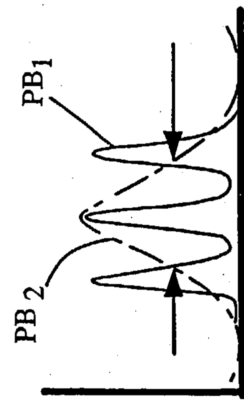


Fig. 3B

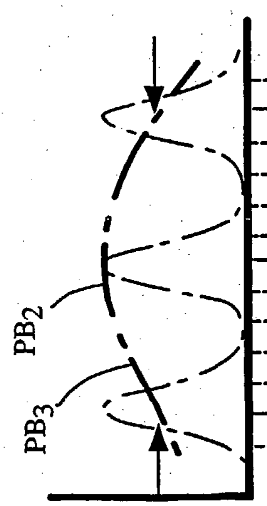


Fig. 3C

Fig. 4A

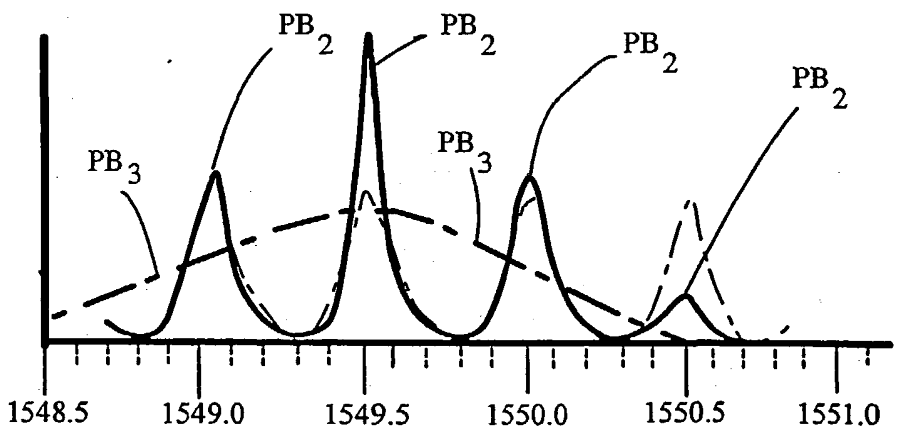


Fig. 4B

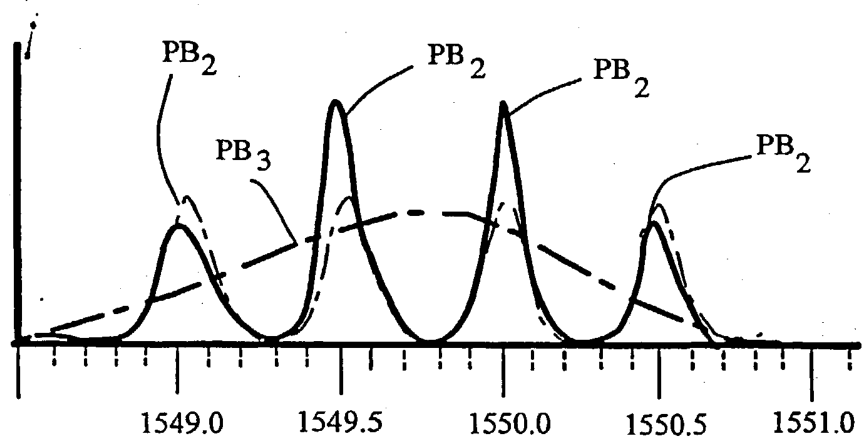
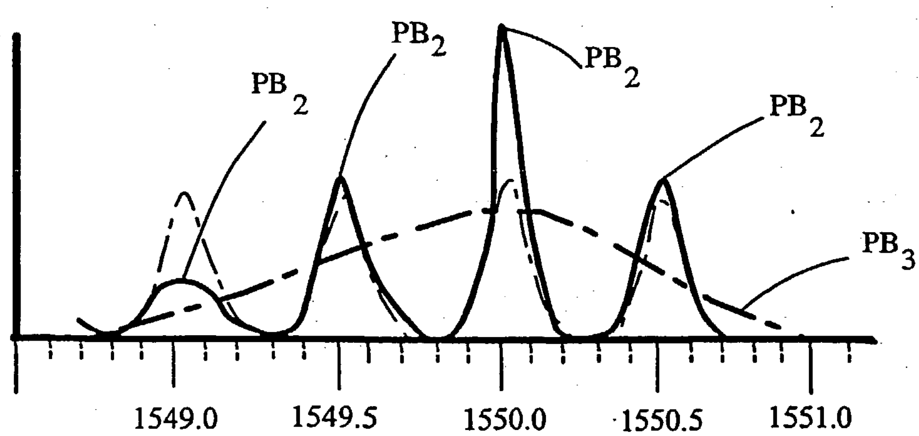
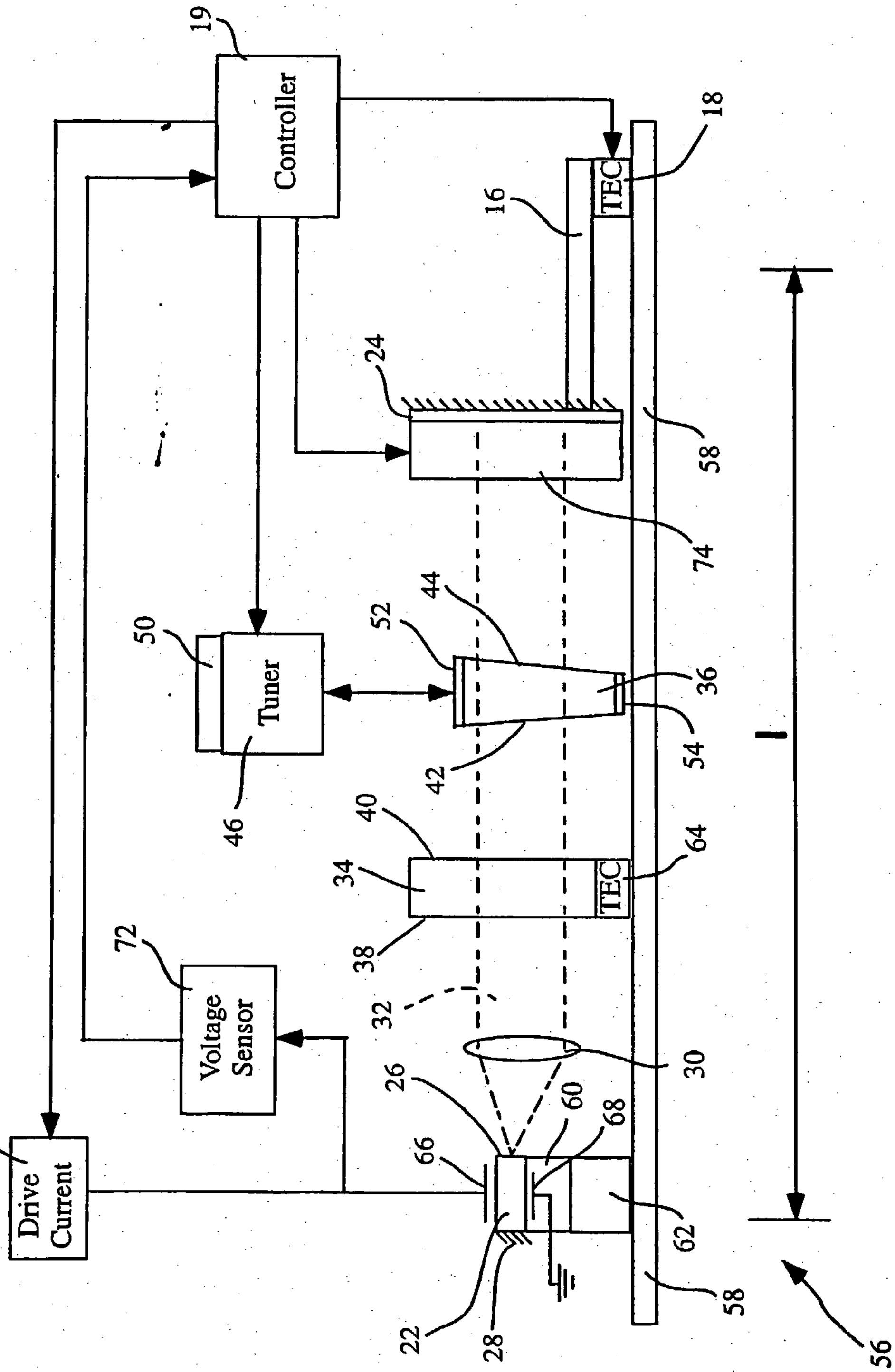


Fig. 4C

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Tuner
Voltage Sensor
Drive Current
TEC
TEC
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32
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70
62
22
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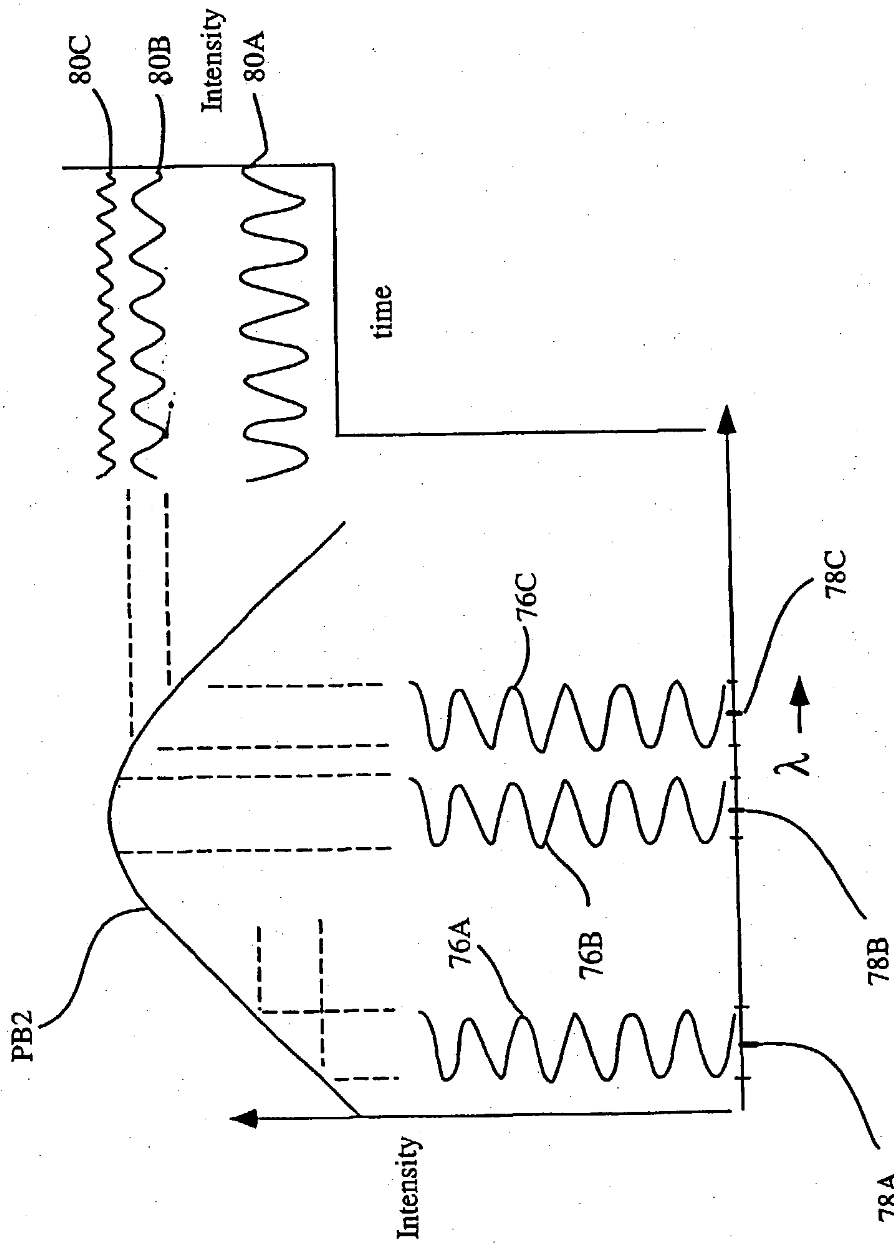
58
56
l

Fig. 5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80B
Intensity
80A
time
PB2
76C
76A
76B
78C
78B
78A
Intensity
λ

Fig. 6

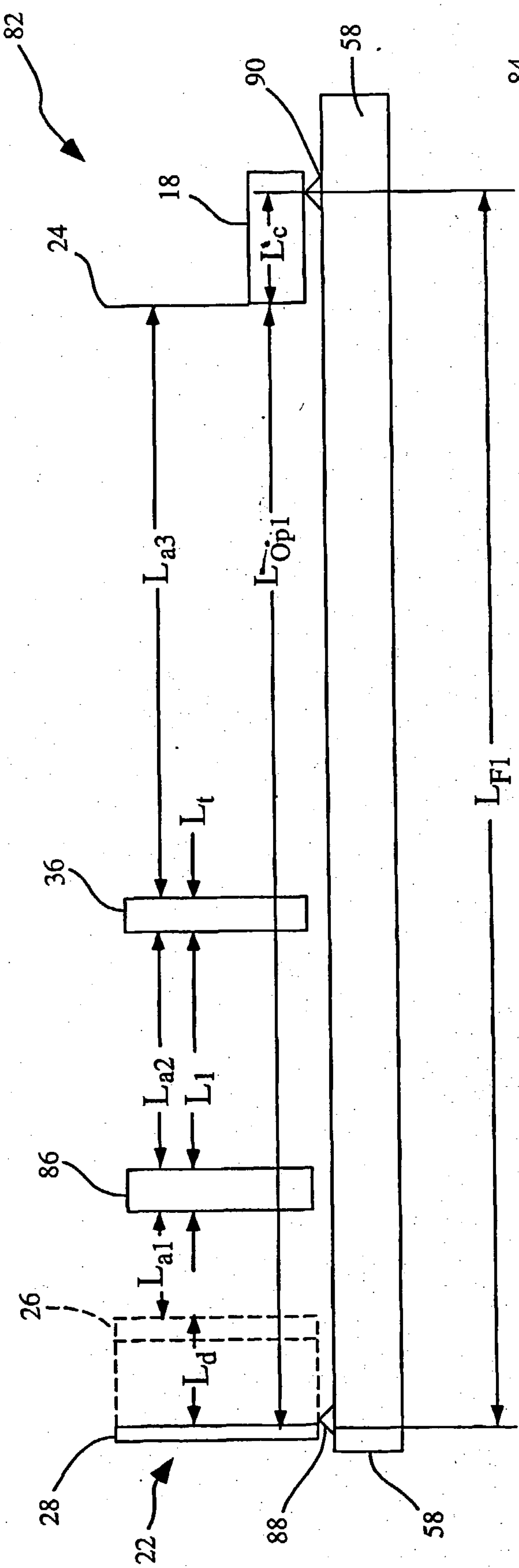
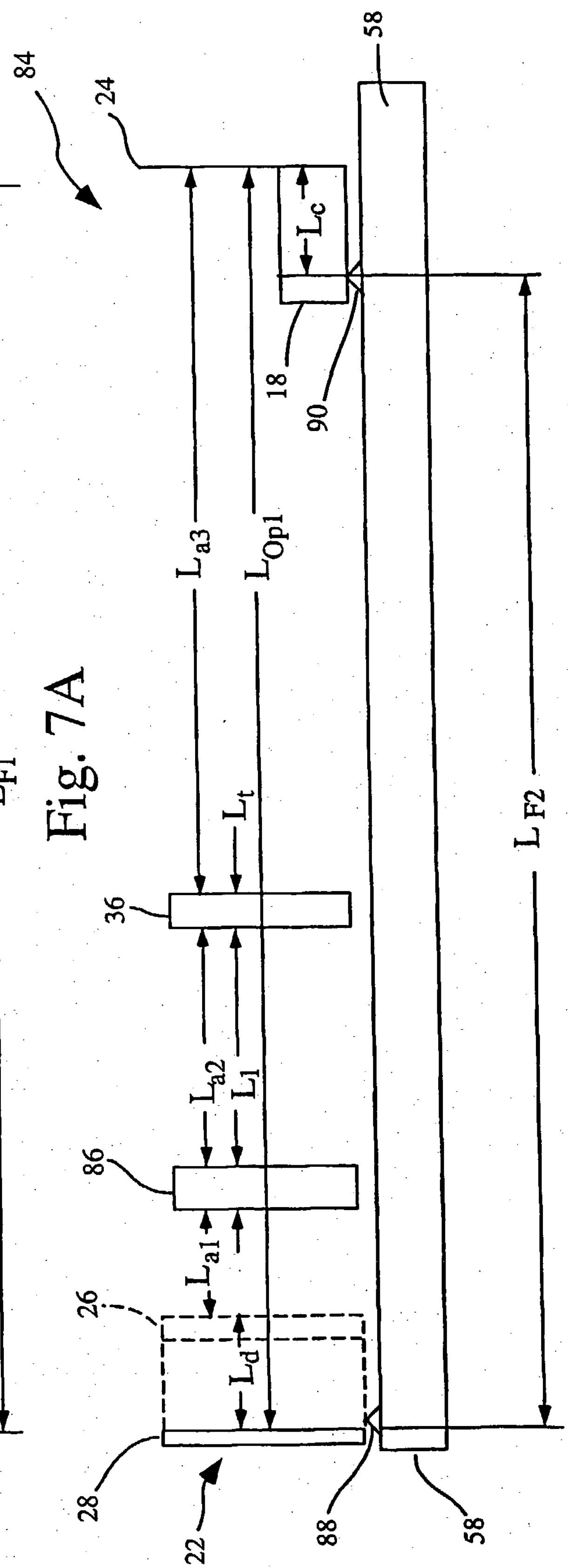

82
90
58
18
24
L_c
L_{a3}
L_{Op1}
L_{F1}
L_t
36
L_{a2}
L_1
86
L_{a1}
26
L_d
28
22
88
58

Fig. 7A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L_c
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L_{a3}
L_{Op1}
L_{F2}
L_t
36
L_{a2}
L_1
86
L_{a1}
26
L_d
28
22
88
58

Fig. 7B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US02/09082

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) : H01S 3/04
US CL : 372/34, 107
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 372/34, 107, 99

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X — Y	US 5,751,750 A (FRIEDE et al.) 12 May 1998 (12.05.1998), Fig. 1-4 and discussion thereof.	1-3, 5-6, 26-27, 39-41 — 4, 7-25, 28-38, 42
Y, P	US 6,229,835 B1 (TOMARU et al.) 08 May 2001 (08.05.2001), col. 1 line 50 - col. 2 line 10.	4, 7, 10-25, 32-38
Y	US 6,040,950 A (BROOME) 21 March 2000 (21.03.2000), abstract, col. 1.	7, 13-14, 20-25, 28, 34, 42
Y	US 6,064,501 A (ROBERTS et al.) 16 May 2000 (16.05.2000), col. 1 lines 53-62, col. 5 lines 10-18.	8-9, 15-17, 29-31, 35-38
Y	US 5,777,773 A (EPWORTH et al.) 07 July 1998 (07.07.1998), col. 1 lines 21-30.	9, 17, 23, 31, 37
Y, P	US 6,215,802 B1 (LUNT) 10 April 2001 (10.04.2001), col. 1 line 41 - col. 2 line 20.	11-12, 14
Y	US 5,428,700 A (HALL) 27 June 1995 (27.06.1995), abstract.	12, 14
Y	US 5,848,092 A (MITSUMO et al.) 08 December 1998 (08.12.1998), Fig. 1 col. 3-4.	13-14, 20-25

Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
05 June 2002 (05.06.2002)	02 AUG 2002
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230	Authorized officer Paul Ip Telephone No. (703) 308-0956